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**Long-term trends in large-scale circulation behaviour and wind storms for
North Atlantic islands: A multi-data analysis using ERA-20C and
meteorological station data**

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Abstract

This research examines the role that large-scale circulation plays in local storminess for the North Atlantic islands of Orkney and Shetland, using the ERA-20C (1900-2009) reanalysis dataset. Automatic Lamb classification is applied to daily mean sea level pressure (MSLP) data at $0.125^\circ \times 0.125^\circ$ resolution, to typify large scale circulation patterns and calculate measures of storminess (frequencies of severe gale days, very severe gale days, and gale days that are not severe), calibrated using available observations from meteorological stations on the islands, obtained through the UK Met Office. Analysis of the reanalysis-based gale day record indicates that while the frequency of cyclonic (C) weather type days does not vary over the study period, this weather type is coinciding more often with gale days, and especially very severe gale days, which may indicate an increase in the intensity of cyclonic weather types in the region.

Keywords: wind storms, climate variability, North Atlantic, islands, Lamb weather typing

1. Introduction

Recent episodes of storminess in the UK, such as the winter of 2013/14, invite speculation as to whether a shift is underway towards more extreme weather (Kendon and McCarthy 2015). Due to their proximity to North Atlantic storm tracks, islands like the Orkneys and Shetland may be particularly impacted by such changes, with a range of environmental, economic and social effects (e.g. Young et al. 2014). Identifying trends in storminess is complex as multiple parameters, including the magnitude, frequency and timing/seasonality of events, may be influenced. Additionally, due to the rarity of extreme events, it is vital to look far into the past to capture the greatest range of variability.

Previous studies highlight the importance of scale, both in time and space, when assessing changes in storminess. For example, based on observed data, Lozano et al. (2004) find that while the total number of cyclones crossing the North Atlantic has decreased slightly during 1965–1995, in Ireland and southern Scotland, there is a trend towards increased winter storminess and calmer summers. Weisse et al. (2005) used a regional climate model to analyse storminess over the eastern North Atlantic from 1958 onwards, and found that storm frequency increased over most of the study domain but later decreased in parts of the study domain. Barring and von Storch (2004) studied Scandinavian storminess since ~1800 using historical meteorological station data and found no significant long-term trends.

Yet, historical climate observations were often not generated with the intention of informing long-term analysis, and as such, data availability and quality can be limiting factors. This is especially the case in remote regions of the world, such as some small islands, where the density of observations may be limited prior to the modern era (Foley 2017). Furthermore, where long-term records do exist, quality control processes are required to ensure that recording and transcription errors are not propagated to any subsequent analysis.

Reanalysis data products, which assimilate available observations to produce long-term, gridded datasets of climate parameters, may be useful (e.g. Laloyaux et al. 2016). A range of reanalysis datasets are available for studying weather and climate variability. NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) dataset (Rienecker et al. 2011) and the updated MERRA-2 (Gelaro et al. 2017) provide data beginning in 1980 and so are less suited to the identification of long-term trends. The NCAR-NCEP reanalysis (Kistler et al. 2001) covers 50 years, while the NCEP Climate Forecast System Reanalysis (CFSR) covers 31 years (Saha et al. 2010). Longer products include the NOAA 20th century reanalysis (Compo et al. 2011) and the European Centre for Medium-Range Weather Forecasts' ERA-20C (Poli et al. 2016). Spatial

resolution also varies; the NOAA 20th century reanalysis is available on $2^{\circ} \times 2^{\circ}$ global grids, while ERA-20C is available at much finer $0.125^{\circ} \times 0.125^{\circ}$ resolution, and therefore likely more suitable for characterising the climate of topographically complex regions such as small islands.

These products, while state-of-the-art, are vulnerable to bias and error. Bengtsson et al. (2004) notes the potential for spurious trends if a non-stationary bias is introduced via the assimilated observations. Studies of extreme windstorms in reanalysis data products have highlighted conflicting trends; for example, a large number of extra-tropical NH and polar windstorms around 1920 in the NOAA 20th century reanalysis is at odds with increasing trends in ERA-20C (Befort et al. 2016). Similarly, Smits et al. (2005) report a decrease in storminess over the Netherlands between 1962 and 2002 based on meteorological station data, which is at odds with reanalysis data, but conclude from an analysis of reanalysis versus station geostrophic wind that inhomogeneities in the reanalysis data are the likely source of error.

The complex spatial dimensions of storm changes necessitate localised study, and potentials for error and uncertainty in both historical meteorological data and modern reanalysis data necessitate the use of multiple kinds of data to facilitate more robust identification of trends. This research develops a multi-data approach to characterise changes in wind storms, and illustrates its application on the North Atlantic islands of Orkney and Shetland.

Automatic Lamb classification is applied to a twentieth century reanalysis data product, ERA-20C, to typify large scale circulation patterns and calculate measures of storminess, which are calibrated using available historical observations. Unlike approaches that identify windstorms in reanalysis datasets based on wind speeds, which tend to be underestimated in reanalysis data products, the automatic Lamb classification approach utilises only mean sea level pressure data, a directly assimilated variable, from the reanalysis product. A potential source of uncertainty when using this approach has been the choice of the gale day threshold parameter; Jenkinson and Collinson's (1977) original choice, though empirically-based, is context-specific, calibrated for the 10-year period 1957-1966 using monthly frequencies of maritime gales around the British Isles. Using the same gale day threshold parameter in other spatiotemporal contexts could yield unreliable results. Therefore, in the present study, historical meteorological datasets from several locations within the study region are used to develop an approach for locally calibrating the gale day threshold parameter in regions of data sparsity.

Relationships between large-scale circulation patterns and wind storm frequency and severity are the explored

using the resultant, reanalysis-based gale climatology, and long-term trends in these relationships are analysed and discussed.

2. Methodology

2.1 Reanalysis and historical data

ERA-20C is a twentieth century (1900-2009) reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts, which assimilates surface pressure and marine wind observations (Poli et al. 2016). This reanalysis is selected here as it has both the temporal coverage to be helpful in characterising extreme events, and the spatial resolution to be relevant on the scale of small islands. Daily mean sea level pressure (MSLP) data was obtained at $0.125^\circ \times 0.125^\circ$ resolution, to which the weather classification method was applied. The dataset commences in 1900. ERA-20C assimilates observations from the International Surface Pressure Databank (ISPD) versions 2.2 and 3.2.6 (Compo et al. 2015), and the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) version 2.5 (Woodruff et al. 2011) historical datasets.

Daily observed meteorological data for stations across the Shetland and Orkney islands were obtained from the UK Met Office. Stations with less than 10 years of data and records that end prior to the start of the ERA-20C dataset, according to Met Office metadata were excluded, leaving a total of 49 stations. A day of gale is counted “when a mean wind speed reaches or exceeds (or is estimated to have reached or exceeded) 34kn over a period of at least several minutes (10 minutes in the case of a station equipped with an anemograph)”¹. Of these, 36 did not contain any gale day flag data (i.e. empty or absent column of data), and 2 contained spurious values (e.g. gale day flag greater than 1), leaving 11 stations with potentially useful data for this analysis. Of these, three stations were found to have digitised records shorter than five years for the relevant parameter, and one contained substantial missing values (at least ~220 days missing in every year); these four stations were also excluded on data quality grounds.

Finally, visual inspection of the annual gale day totals at each station revealed one station with totals of approximately twice the other stations for a period in the late 1970s. Totals are in line with other stations for the remainder of the record at this station. Although data quality flags indicate that this data underwent full Met Office QC checks, this data was excluded as a data processing error could not be ruled out as a possible reason

¹ MIDAS metadata: https://artefacts.ceda.ac.uk/badc_datadocs/ukmo-midas/WD_Table.html

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for this discrepancy. In total, therefore, six stations across the Orkney and Shetland Islands were used in the analysis (Figure 1).

To take account of spatial heterogeneity, data from all meteorological stations was combined into a single dataset, representing days when a gale day was recorded at any meteorological station in the region.

2.2 The automatic Lamb weather type classification method

The Lamb weather type classification method (Lamb 1972) is based on the variation in surface pressure values around the British Isles, but can be applied to any mid-to-high latitude region (Jones et al. 2013). An automatic Lamb classification (Jenkinson and Collison 1977) uses a set of simple rules applied to gridded pressure maps to determine westerly flow, southerly flow and so forth. Applications of the technique include the development of rainfall scenarios for southeast Spain (Goodess and Palutikof 1998), and the analysis of pressure patterns in southern Scandinavia (Linderson 2001). The method has been used to study trends in gale days in the Falkland Islands (Jones et al. 2016).

Unlike Lagrangian (Wernli and Davies 1997; Tamarin-Brodsky and Kaspi 2017; Lukens et al. 2017) and Eulerian methods, which can be used to infer changes in storm track behaviour from reanalysis data, the Lamb method only diagnoses storm occurrence and magnitude. The Eulerian approach calculates the variance of filtered geopotential height, vorticity, etc., diagnosing areas of large band-passed variance as stormtracks (Blackmon 1976; Blackmon et al. 1977), while the Lagrangian approach is based on the identification and tracking of local minima in the geopotential height field itself (Blender et al. 1997; Hoskins and Hodges 2005). The relative utility of the Lamb method is its low computational cost, its reliance on a directly assimilated reanalysis variable (MSLP) rather than a purely modelled variable, and the ability to compare and tune with historical observations.

To apply the Lamb method, a grid centred on the Shetland and Orkney Islands is developed (Figure 2). MSLP data in units of hPa is interpolated to each point, using triangulation-based linear interpolation. The equations outlined, adapted from Jones et al. (1993), are used to identify flow features, based on these points:

$$W = \frac{1}{2}(12 + 13) - \frac{1}{2}(4 + 5) \quad (\text{westerly flow})$$

$$S = \frac{1}{\cos(\phi)} \left[\left(\frac{1}{4}(5 + 13 + (2 \times 9)) \right) - \left(\frac{1}{4}(4 + 12 + (2 \times 8)) \right) \right] \quad (\text{southerly flow})$$

$$\text{If } W > 0, D = 90 - \tan^{-1}(W/S)$$

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If $W < 0$, $D = 270 - \tan^{-1}(W/S)$ (wind direction)

$F = (S^2 + W^2)^{1/2}$ (resultant flow type)

$$ZW = \frac{\sin(\phi)}{\sin(\phi - 2.5^\circ)} \left[\frac{1}{2}(15 + 16) - \frac{1}{2}(8 + 9) \right] - \frac{\sin(\phi)}{\sin(\phi + 2.5^\circ)} \left[\frac{1}{2}(8 + 9) - \frac{1}{2}(1 + 2) \right]$$

(westerly shear vorticity)

$$ZS = \frac{1}{2 \cos(\phi)^2} \left[\frac{1}{4}(6 + 14 + (2 \times 10) - \frac{1}{4}(5 + 13 + (2 \times 9) - \frac{1}{4}(4 + 12 + (2 \times 8) + \frac{1}{4}(3 + 11 + (2 \times 7) \right]$$

(southerly shear vorticity)

$Z = ZW + ZS$ (total shear vorticity type)

where

ϕ = the bisecting latitude of the analysis grid, 60° .

Note: $\underline{2}$ is a multiplier, not a point reference.

The eight pure Lamb weather types are then classified as follows:

i) Pure directional types (N, S, E, W, NW)

If $|Z| < F$, flow is essentially straight, corresponding to a pure directional type. Direction is calculated based on an 8-point compass. There are 5 pure directional types, N, S, E, W and NW, which Lamb (1972) considered sufficiently distinct as to merit its own type. Thus, NW is not a directional hybrid, but a separate type. SW, SE and NE flows contribute equally to their major types; e.g. a NE flow contributes 0.5 to both N and E.

ii) Pure synoptic (cyclonic and anticyclonic) types (A, C)

If $|Z| > 2F$ and $Z > 0$, the pattern is strongly cyclonic (C). If $|Z| > 2F$ and $Z < 0$, the pattern is strongly anticyclonic (A).

iii) Synoptic/directional hybrid types

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If $F < |Z| < 2F$, the flow is partly cyclonic or anticyclonic, corresponding to a synoptic/direction hybrid. These are categorised as contributing equally to their major types; e.g. an ANE flow contributes 0.33 to A, N and E individually.

iv) Unclassified type (U)

If $F < 3$ and $|Z| < 3$, there is a light, indeterminate flow, categorised as unclassified (U).

2.3 Gale indices and calibration

Jenkinson and Collison (1977) define a gale day (GD) as occurring when $G = (F^2 + (0.5Z)^2)^{1/2}$ is greater than 30. If $G > 40$, this is defined as a severe gale day (SGD), and if $G > 50$, this is defined as a very severe gale day (VSGD). These thresholds were calibrated for the 10-year period 1957-1966 using monthly frequencies of maritime gales around the British Isles and as such, may not be suitable for different regions and datasets. Jones et al. (2016), which applied the approach across the Falkland Islands, also with a calculation grid of 2.5° latitude and longitude resolution, halve these gale day thresholds, such that a gale day is defined as $G > 15$. Jones et al. (1999) used 5° latitude \times 10° longitude data, and selected threshold values of between 32 and 40 to define severe gale days. Donat et al. (2011) define gale days for Central Europe using a threshold of $G > 35$, which approximates the number of extreme and destructive storm events for that study region, although calibration to the record of destructive storm events could lead to underestimation of gale days that were less severe.

Here, the gale day threshold is calibrated using the combined observational dataset, which represents days when a gale day was recorded at any meteorological station in the region. The threshold is varied until agreement between the annual counts of observed and reanalysis-based gale days for the period covered by observations, quantified using the Nash-Sutcliffe efficiency (Nash and Sutcliffe 1970), is maximised. This metric considers both association and distance between the datasets, unlike correlation coefficients which may return a higher score based solely on the similarity of interannual temporal patterns despite over/underestimation of the observed counts.

The magnitude of interannual variability in gale day counts is also compared using the standard deviation of the annual counts.

For clarity, gale days that are not classed as severe or very severe gale days are referred to in figures as 'gale days (not severe)', abbreviated to GD(NS).

2.4 Annual and decadal trend analysis

To identify whether gale days are changing in frequency, trends are quantified using Spearman's correlation coefficient, ρ , to measure the strength and direction of association between two sets of data: time and climate parameters. Significant trends at $p < 0.05$ are denoted with * throughout.

Both annual and decadal trends are calculated, for all gale days and for the three subclasses of gale day severity generated based on the reanalysis data. Decadal trends in the occurrence of different Lamb weather types are also assessed. Again, significant trends at $p < 0.05$ are denoted with * throughout. To characterise how large-scale circulation changes may be impacting trends in gale days, the Lamb weather type associated with each gale day is identified.

Given issues with homogeneity in long reanalyses, it is important to consider whether any increasing trend is related to the increasing number of observations assimilated into the reanalysis over time. To examine this possibility, annual gale day counts are plotted against the total number of surface pressure measurements assimilated to create the ERA-20C dataset for the study domain. *k*-means clustering is used to partition gale days into data-sparse vs data-rich periods and trends within these clusters are discussed.

3. Results

3.1 Annual gale day counts and interannual variability

Gale day counts are variable across the region. Based only on years with complete records, the two stations located on Orkney, Kirkwall and Loch of Hundland, experience on average 30 and 13 gale days per year respectively. The differences may be explained by their geographies; Loch of Hundland is inland, while Kirkwall is situated on the coast. At the more exposed site of Sule Skerry, this increases to 39. Shetland, Baltasound, Lerwick, and Sumburgh average 46, 44 and 48 gale days per year.

The spatial heterogeneity of windstorms is such that that specific days identified as gale days may not be the same at each station, even when annual totals are similar. The combined dataset, representing days when a gale day was recorded at any meteorological station in the region, averages 64 gale days per year, which is more than is recorded for any individual site. The magnitude of interannual variability for the combined dataset, quantified using the standard deviation, is 16 days.

Setting the gale day threshold to the default $G > 30$, as per Jenkinson and Collison (1977), results in an underestimation of gale days based on ERA-20C reanalysis data (Figure 3). There is a substantial decrease in

the number of observed gale days in the 2000s, for which meteorological station coverage is sparser with just two stations recording in this period, therefore the calibration procedure is followed both including and excluding this data. Setting the gale day threshold G to 24 maximises the Nash-Sutcliffe efficiency for the both periods ($NSE_{1900-2009} = 0.1$; $NSE_{1900-1999} = 0.15$). While setting G to 25 maximises the metric for 1900-2009 and results in a slightly higher $NSE_{1900-2009}$ of 0.16, it also results in a negative value for $NSE_{1900-1999}$. Therefore, a gale day threshold G of 24 is selected. The study was entirely reproduced with G set to 25, also, and the major conclusions that will be presented for C, E, and CE events remain.

This threshold value results in an average of 62 gale days per year with a standard deviation of 13.3, based on the ERA-20C reanalysis data over the period that overlaps with observations (Figure 3). While application of the Lamb classification technique to the reanalysis data produces annual gale day counts and interannual variability of a similar order of magnitude to the available observations across the region, the patterns of interannual variability are different. These statistics indicate that the ERA-20C reanalysis can capture the summary statistics of gale days in the Scottish Isles, and has the potential to yield insights into long-term trends, though there is likely to be uncertainty associated with the representation of individual storm events.

3.2 Annual and decadal gale day trends

Meteorological station records are mostly too short to reliably diagnose long-term trends. At the stations with the longest records, trends are inconsistent (Kirkwall: $\rho = 0.36^*$; Lerwick: $\rho = 0.02$). The maximum period available at each station was used to estimate these trends, which are not the same at each station. When the overlapping period of available observations at each station is used, the discrepancy remains (Kirkwall: $\rho = 0.36^*$; Lerwick: $\rho = 0.1$), highlighting the highly local character of gales, and the potential usefulness of the reanalysis records in describing regional climate.

Statistically significant annual trends in gale day counts are identified in the reanalysis-based timeseries (GD(NS): $\rho = 0.44^*$; SGD: $\rho = 0.31^*$; VSGD: $\rho = 0.38^*$; All: $\rho = 0.48^*$). When annual gale day counts are plotted as anomalies relative to 1900-2009 (not shown), it becomes apparent that the earlier half of the 20th century is less active in terms of gales. Calculation of decadal trends quantifies this shift (GD(NS): $\rho = 0.78^*$; SGD: $\rho = 0.74^*$; VSGD: $\rho = 0.87^*$; All: $\rho = 0.85^*$), illustrated in Figure 4.

For each Lamb weather type, decadal totals are also calculated. There are increasing trends in the prevalence of N ($\rho = 0.84^*$) and E ($\rho = 0.82^*$) types, compensated for by decreasing trends in the frequency of A ($\rho = -0.3$), C

($\rho = -0.11$), S ($\rho = -0.19$), W ($\rho = 0.01$), NW ($\rho = -0.48$) and U ($\rho = -0.44$) types. Figure 5 depicts both interannual Lamb weather type day anomalies (black) and average anomalies for each decade (red) for each Lamb weather type, illustrating these trends.

3.3 Relationships between Lamb weather type and reanalysis-based gale day trends

When Lamb types components associated with each gale day are identified and tabulated (Table 1), it is evident that gale days most commonly coincide with Lamb types that have a W, C or E component. Therefore, to investigate relationships between Lamb weather type and reanalysis-based gale day trends, decadal change in the frequency of gale days associated with W, E, C, CW and CE types are quantified (Table 2).

A contrast emerges between the C and E types, with the C types associated with strongest trend in VSGDs, and the E type associated with the strongest trend in GD(NS). Significant trends are also identified for the W- and CW-GD(NS) combinations, and for C- and E-SGD combinations. The CE-VSGD combination was also associated with a statistically significant trend.

There is no significant trend in the frequency of C type days across 1900-2009, yet the coincidence of gale days with C type days is increasing. To quantify this change in gale intensity associated with a weather type, a simple intensity metric is calculated for each year as $\frac{\sum G_X}{\sum X}$ where X = Lamb type. A monotonic trend is evident in this metric for both weather types, which is stronger for the pure C type ($\rho = 0.58^*$) than for the E ($\rho = 0.4^*$), W ($\rho = 0.35^*$), CE ($\rho = 0.37^*$) or CW ($\rho = 0.32^*$) types.

3.4 Relationship between gale day trends and number of assimilated observations

Homogeneity is a recognised issue in long reanalyses; for example, Krueger et al. (2012) find inconsistencies in 20CR-derived and observation-derived storm trends in Northern Europe and the northeast Atlantic, indicative of inhomogeneities in earlier years of that reanalysis. As such, it is important to consider the reliability of increasing gale day trends, as such trends may also relate to the increasing number of observations assimilated into the reanalysis over time.

For each year, gale day counts were plotted against the total number of surface pressure measurements assimilated to create the ERA-20C dataset for the domain centred on Orkney and Shetland (Figure 6, left); two clusters are apparent, which were partitioned using *k*-means clustering. These same clusters were then identified in a time-series plot (Figure 6, right). When the data is divided into the measurement-dense modern period and

measurement-sparse earlier period, and a linear fit overlaid on each period, it is evident that the number of gale days is declining in the former and increasing in the latter, suggesting that increasing availability of observations cannot alone explain the trends in gale day occurrence identified over the study period. The major change from measurement-sparse to measurement-rich periods in this domain is visible in timeseries plots of measurement availability, also (Figure 7).

4. Discussion

An increase in the frequency of gale days of all severity was identified in the reanalysis data. Results also indicate an increase in intensity of cyclonic circulation patterns over the 20th century across Orkney and Shetland. No increasing trend was identified in the proportion of C type days across 1900–2009, but this weather type is more frequently coinciding with gale days, and especially VSGDs. Conversely, GD(NS) associated with E type days are increasing in frequency, but so too is the proportion of E type days. These results suggest that the mechanisms driving changes in frequency of the most severe gales are different to those driving changes in the frequency of minor gales. The different mechanisms for E type GD(NS) and C type VSGD trends may be interpreted as changes in cyclone positioning in the case of the former versus cyclone strengthening in the case of the latter.

While exploring these mechanisms in depth is outside of the scope of this paper, further research will explore several lines of enquiry. For instance, anthropogenic climate change leading to a warmer and moister climate may yield stronger midlatitude storms, as indicated in some modelling experiments (e.g. Booth et al. 2013; Willison et al. 2015). Another mechanism to be explored is poleward shifting and intensification of storm tracks, which some models suggest can be anticipated this century (Yin 2005), and which would likely contribute to the trend in C type VSGD. Regional heating in the high latitudes and subsequent connections between Arctic and mid-latitude weather will also be explored (Overland and Wang 2018).

Variability in the North Atlantic Oscillation, alongside long-term warming and sea-ice changes, may also play a role in influencing North Atlantic storm tracks, as noted in the paleoclimate study of Orme et al. (2017). Donat et al. (2010) found that over Central Europe, negative NAO phases are associated with easterly flow types, which has relevance for the trends in E type GD(NS) identified here over Orkney and Shetland.

There is a noticeable increase in gale days for the 1970s–1990s. Feser et al.'s (2015) review of literature on North Atlantic storminess found that most storm trends derived from reanalyses data and historical climate

model data identify a similar increase from the 1970s until the mid- 1990, and that this signal is also represented in long-term proxies (e.g. forest damage) and the North Atlantic Oscillation index, suggesting that this signal is decadal variability associated with the NAO, rather than an artefact of increased accuracy in the reanalysis data for the modern period. Wind speed measurements from Switzerland follow a similar pattern, with increasing maximum wind speeds since the 1970s (Usbeck et al. 2009).

The results of the research presented here also highlight the challenges of characterising extreme weather risks in remote, data-sparse geographies. While every effort was made to identify and discount potentially unreliable observational data, it is possible that human error at the time of recording or in the digitisation process could have introduced spurious values. Furthermore, the brevity of station records for the locations under investigation is a limiting factor for the calibration of the reanalysis-based gale day record, as well as trend identification. Analysis of historical data sources can assist in augmenting our understanding of past weather and climate in remote locales.

Improved data assimilation techniques, computational resolution, and data rescue of historical observations may all contribute towards improving the representation of these types of events in reanalysis data.

5. Conclusions

This research illustrates a multi-data approach combining historical meteorological data and reanalysis data to investigate long-term relationships between large-scale circulation patterns and wind storm frequency and severity. Errors relating to the representation of windstorms in reanalysis data are bypassed by using the automatic Lamb classification approach, which uses only MSLP data. Results suggest an increase in intensity of cyclonic circulation patterns over the 20th century across Orkney and Shetland. The proportion of C type days has remained consistent across 1900-2009, compared to other weather types which experienced statistically significant increasing trends, but this weather type is more frequently coinciding with gale days, and especially VSGDs. Such shifts in the wind storm climate of the region could have profound physical impacts (e.g. property damage, disruption to communication and transportation networks), as well as non-material and cultural impacts. Shifts in the frequency of minor gales are also identified. Although exposure to such events is but one component of impacts analysis, and contextual vulnerability and adaptive capacity must also be considered, understanding these contemporary trends in storminess can provide a vital baseline to assist in anticipating future risks. Further research will focus on applying the automatic Lamb classification method to Coupled

Model Intercomparison Project Phase 5 (CMIP5) data (Taylor et al. 2011), to ascertain how these trends may evolve under future climate scenarios.

Figures

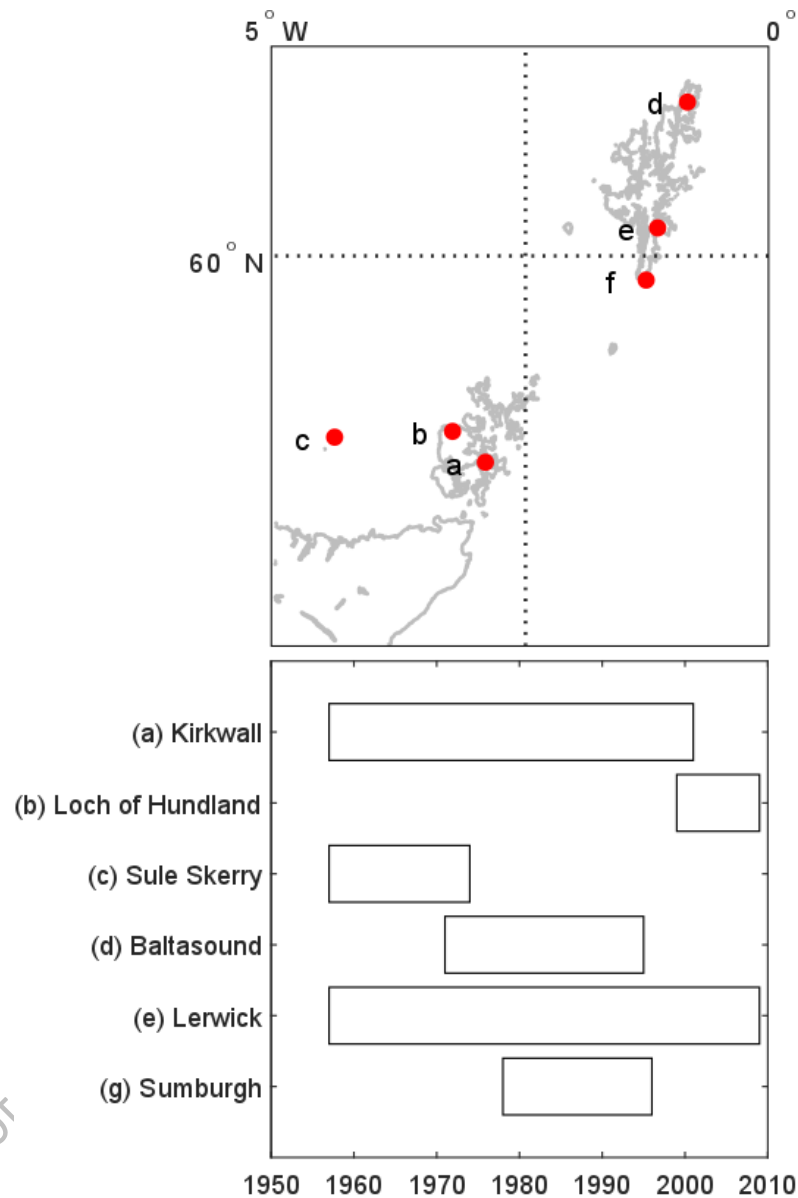


Fig. 1 Location (top) and data availability up to 2009 (bottom) for the stations Kirkwall (a), Loch of Hundland (b), Sule Skerry (c), Baltasound (d), Lerwick (e) and Sumburgh (f)

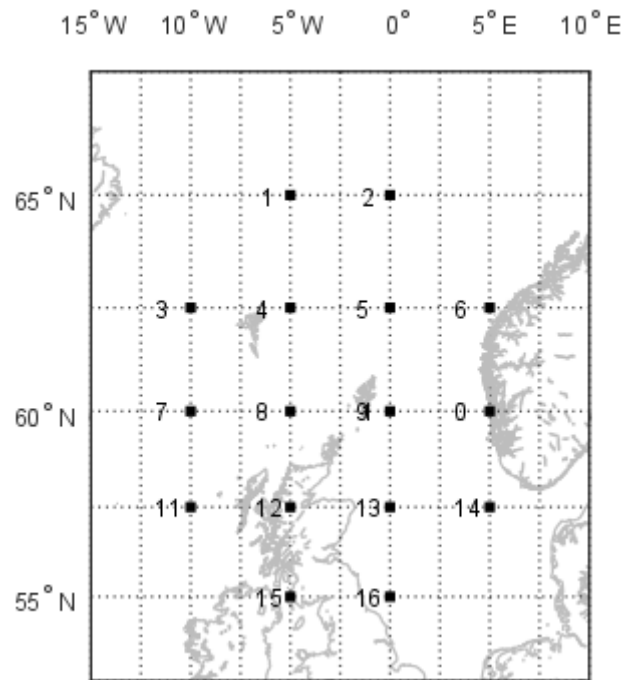


Fig. 2 Locations of the numbered grid points over the Shetland and Orkney Islands used in the application of the automatic Lamb classification method

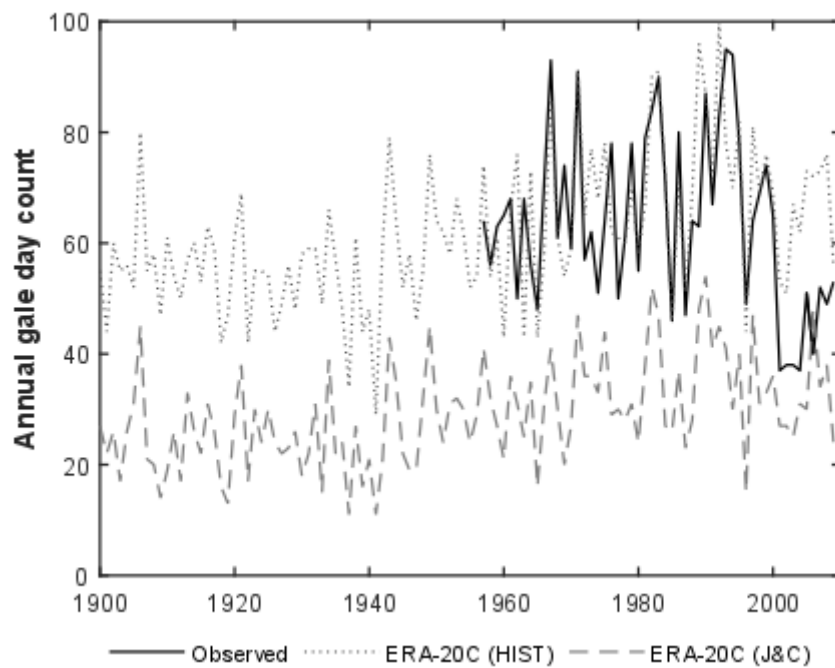


Fig. 3 Annual gale day counts based on analysis of the ERA-20C reanalysis dataset using the Jenkinson and Collinson gale day threshold (grey dashed line) and a historical observation-based gale day threshold (black dashed line) compared with observations (solid line)

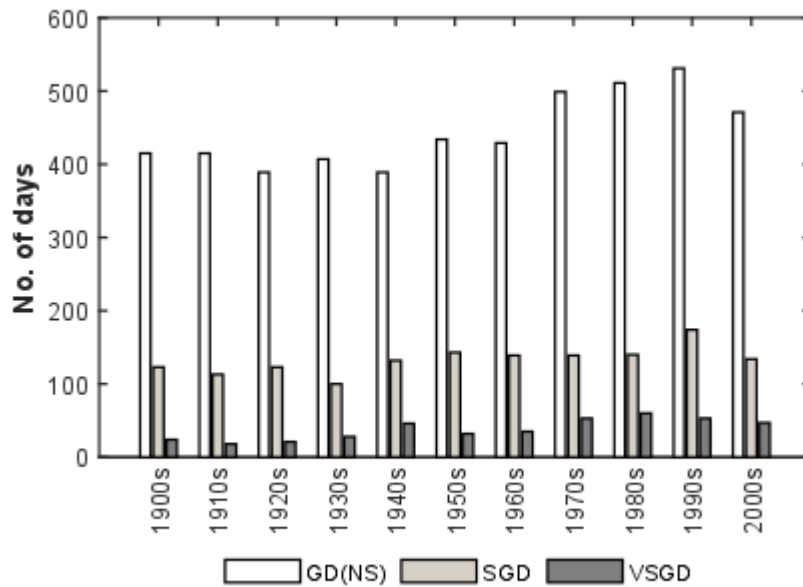


Fig. 4 Decadal counts of not severe (GD(NS)) severe (SGD) and very severe (VSGD) gale days based on classification using the ERA-20C reanalysis data

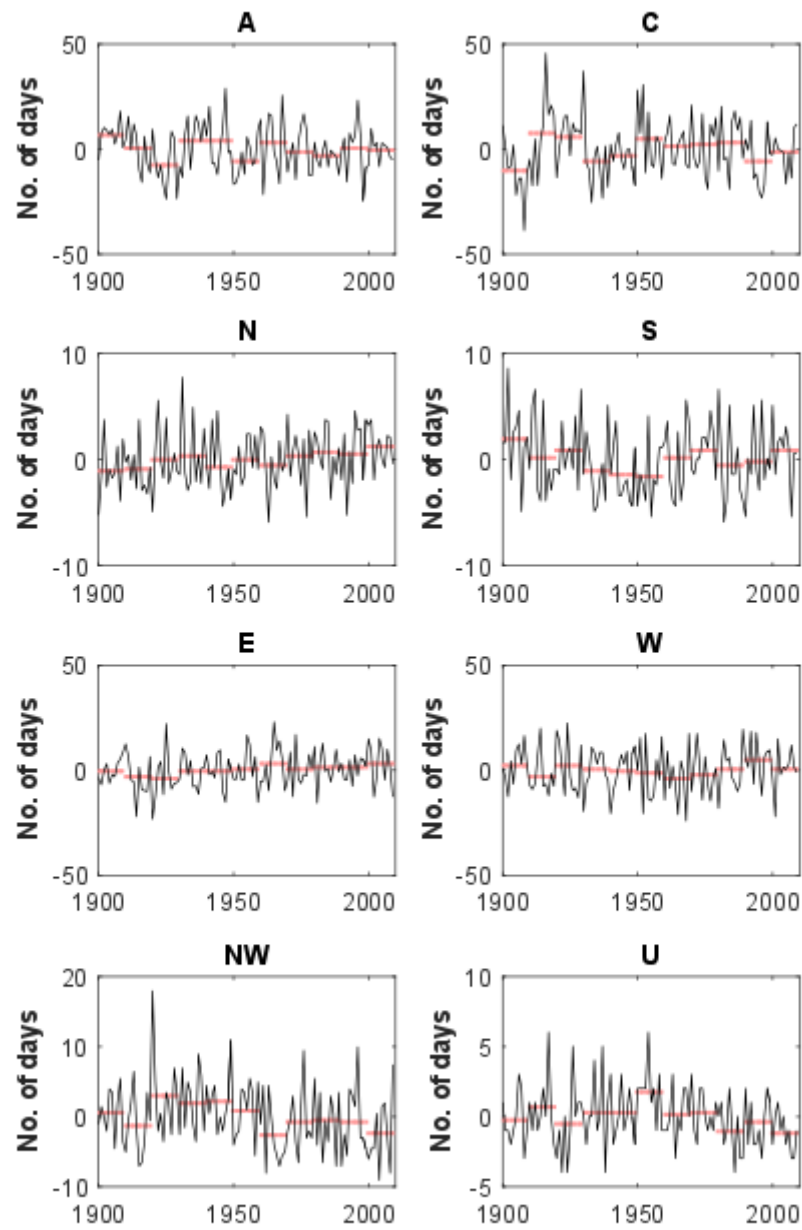


Fig. 5 Interannual Lamb weather type day count anomalies (black) and average anomalies for each decade (red) for each Lamb weather type

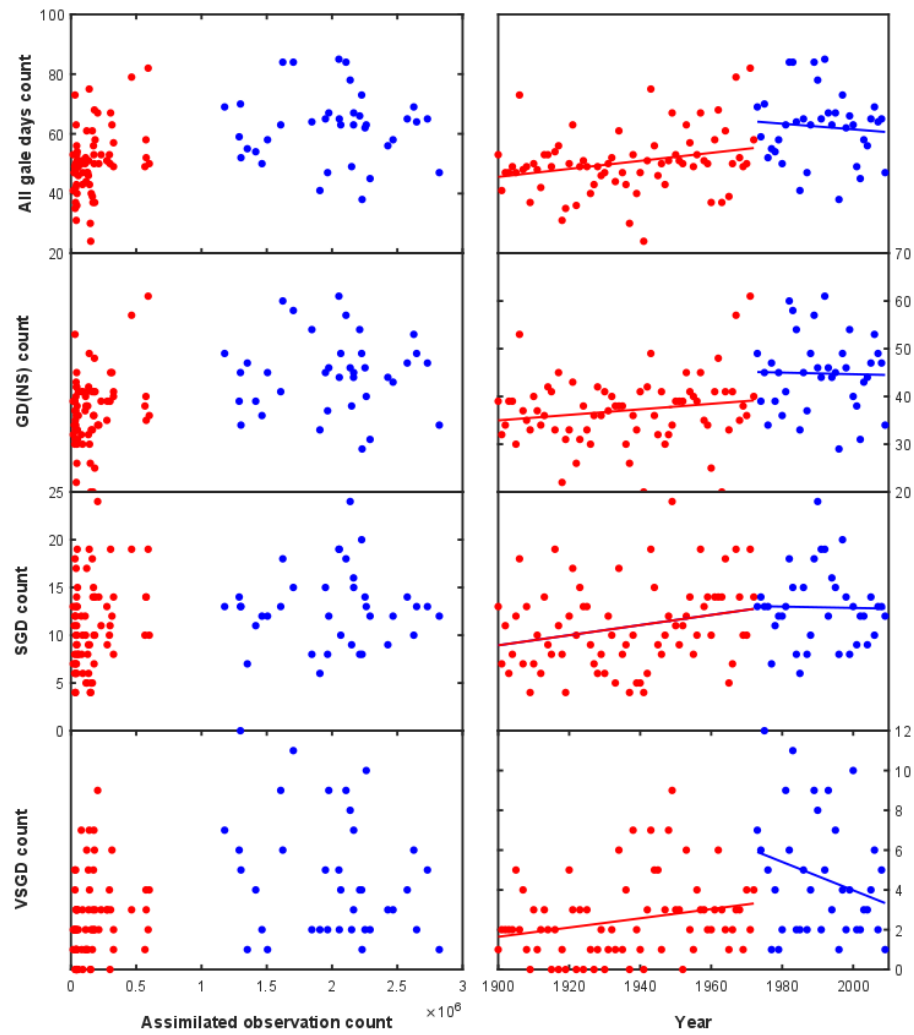


Fig. 6 Annual gale day counts versus total number of surface pressure measurements assimilated in the study domain, partitioned using *k*-means clustering into data-sparse (red) and data-rich (blue) clusters (left) and annual gale day counts over time with same data availability clusters highlighted (right)

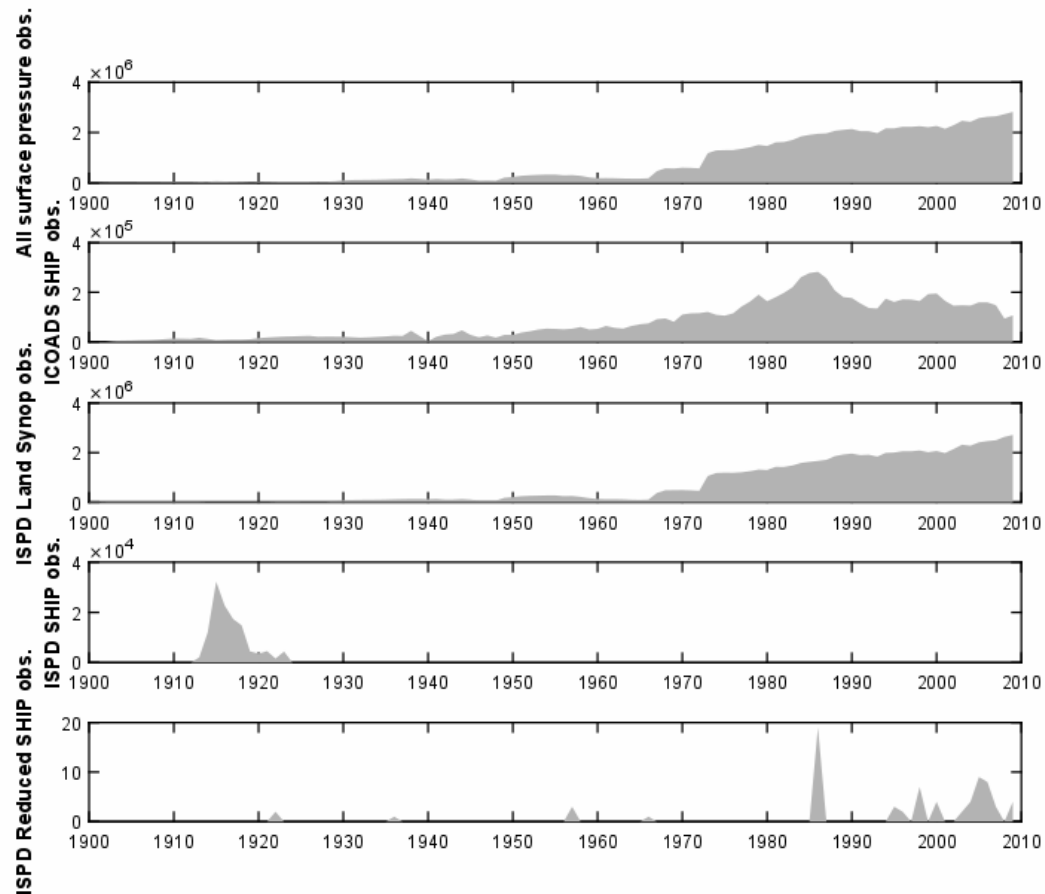


Fig. 7 Number of observations assimilated into ERA-20C reanalysis over time

	<i>A</i>	<i>C</i>	<i>N</i>	<i>S</i>	<i>E</i>	<i>W</i>	<i>NW</i>	<i>U</i>	<i>Total</i>
Gale days (not severe)	221	1544.67	7.67	1.5	826.67	1741	21.5	0	4364
Severe gale days	20	424.17	1.17	0	254.17	569.5	1	0	1270
Very severe gale days	1	134.5	0	0	75	141.5	0	0	352
									5986

Table 1 Number of gale days associated with each Lamb weather type

	<i>C</i>	<i>W</i>	<i>CW</i>	<i>E</i>	<i>CE</i>
Gale days (not severe)	0.62*	0.64*	0.68*	0.75*	-0.01
Severe gale days	0.73*	0.2	0.29	0.69*	0.27
Very severe gale days	0.95*	0.56	0.43	0.52	0.66*

Table 2 Decadal trends in the frequency of gale days associated with the C, W, CW, E and CE types, quantified using the Spearman correlation coefficient (trends found to be significant at $p < 0.05$ are marked with *)

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